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INVESTIGATIONS OF

AIR-TO-AIR HEAT PUMPS FOR MILITARY HOUSING

by

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ABSTRACT

The National Bureau of Standards has performed laboratory and field studies of electric air-to-air heat pumps as a part of the technical investigations sponsored by the three agencies of the Department of Defense. These studies have developed information on the coefficient of performance and heating and cooling capacities of typical systems used for residential applications, design data useful for estimating energy usage and maximum power demand for similar installations, some information relative to the unexpectedly high rate of motor-compressor failure, and comparisons of the annual cost of year-around air conditioning using heat pumps and gas heating systems combined with conventional air conditioners for cooling. The annual cost of heating and cooling these military houses with air-to-air heat pumps averaged about $100 for a unit electric energy cost of 0.8¢/Kwh.

Key Words: air-to-air heat pumps, residential air conditioning, energy usage, annual energy cost.

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The U. S. Air Force began using air-to-air heat pumps for year-around air conditioning of family housing in about 1957. Approximately 10,000 units have been installed at eight air bases in the southeastern states, ranging from North Carolina to Florida, and from the east coast to Arkansas. Most of these houses were of two or three bedroom design, either detached or in duplex relationship. They were typically of one-story construction with a slab-on-grade concrete floor, frame or brick veneer sidewalls, with insulation used in the wall and ceiling construction. The floor area of most of these houses ranged from 1000 to 1200 sq. ft. with a few as large as 2000 sq. ft.

An air-to-air heat pump contains the same basic refrigeration circuit as the conventional window air conditioner; that is, it has a motor-compressor unit, two finned heat exchangers, and a valve or other device for controlling the rate of refrigerant flow in the pipe circuit. The arrangement of the apparatus in an air-to-air heat pump is illustrated in Fig. 1. During summer operation the unit functions exactly like a conventional air conditioner designed for cooling only. The indoor heat exchanger absorbs heat from the indoor air and using the refrigerant as a heat transfer medium, this heat is discharged outdoors through the other heat exchanger. During winter operation the functions of the two heat exchangers are reversed by means of a four-way valve, whereupon the outdoor heat exchanger absorbs heat from the outdoor air and discharges it as warm air from the indoor heat exchanger. All of the apparatus in an air-to-air heat pump can be packaged in a single unit like the 3- and 5-ton package units commonly used in restaurants and stores. However, in most of the Air Force installations, the apparatus was divided into two units. In such a split system the compressor, one heat exchanger, a blower, a flow control device, and the four-way valve are enclosed in a cabinet mounted on a base outdoors near the house, whereas the other heat exchanger, a blower, a flow control device, and usually some auxiliary heaters are enclosed in a cabinet, mounted in the attic or a utility closet, and connected into a duct system for air distribution. The two parts of the split system are connected by two copper refrigerant lines, 25-feet long more or less depending on the location of the units, to complete the refrigerant circuit. The split system was new in 1957, and the Air Force installations were among the first commercial applications.

The National Bureau of Standards has performed a variety of laboratory and field studies of air-to-air heat pumps as a part of the technical investigations sponsored by the three agencies of the Department of Defense. These have included:

(a) Laboratory tests[1/] of stock models of heat pumps to determine compliance with purchase specifications and to provide better understanding of the technical characteristics of air-to-air heat pumps.

(b) An analysis[2/] of electric energy usage and electric power demand data for 16 houses at Little Rock Air Force Base equipped with heat pumps, water heaters, cooking ranges, clothes dryers, and miscellaneous devices, all operated by electricity.

(c) Field studies of the heating performance[3/] of the air-to-air heat pumps in five representative houses at each of two air bases.

(d) Field studies of the annual energy usages in five houses at each of three air bases in which year around air-conditioning was provided by air-to-air heat pumps, and an equal sampling of houses and sites where electric air conditioners were used for summer cooling and gas was used for house heating, water heating, and cooking.

(e) Laboratory analysis of the causes of compressor failure in the field and of certain preventative service practices for alleviating this problem.

(f) Drafting of more adequate specifications for air-to-air heat pumps.

Some of the design problems that have been investigated during these studies are:

(1) Selection of the proper balance point and the correct amount of supplementary electric resistance heating for a given application.

(2) Calculation of the design heating load for residential buildings.

(3) Maintaining a suitable coefficient of performance in actual use.

(4) Obtaining the proper relation between the surface areas in the two heat exchangers and in the two capillary tubes.

(5) Providing adequate defrosting.

(6) Selection of controls for defrosting, activation of supplementary heaters, and overload protection.

Some of the installation problems found during these studies were:

(1) Accessibility of the indoor units in attic installations.

(2) Air leakage of the duct system.

(3) Location of the indoor thermostat.

Various operational and technical problems occurred, such as:

(1) Frequency of failure of compressor-motor unit.

(2) Estimation of total energy usage.

(3) Control of maximum electric demand.

(4) Economic comparison of all electric heat pump systems with gas-electric combinations for year around air conditioning.

The investigations of a few of these problems by the Bureau will be discussed and some examples given.

A characteristic of a compression-refrigeration system is that the capacity of the system decreases as the temperature difference between the indoor and outdoor environments increases. This is approximately a linear relationship. The design indoor-outdoor temperature difference rarely exceeds 25°F during summer operation of an air-to-air heat pump, but may be in the range from 40°F to 70°F during winter operation in the geographical areas mentioned above. Hence the heating capacity of the heat pump is lower than the cooling capacity at the respective design conditions and the heating capacity becomes decreasingly lower as the heating requirement increases. The outdoor temperature at which the heating capacity of a heat pump exactly equals the heat loss of the house is called the "balance point." The balance point for heat pump installations in residences is usually selected at a temperature higher than the design winter outdoor temperature, and one or more electric resistance heater elements are installed in the indoor unit to provide the additional heating capacity needed during the short periods of cold weather.

The laboratory data illustrated in Figure 2 shows that the relation of heating capacity to outdoor temperature was linear for units employing expansion valves, but that the capacity drooped at higher outdoor temperatures for units equipped with a capillary tube as a refrigerant flow control. The heating capacity at an outdoor temperature of 20°F ranged from 55 to 73 percent of that at an outdoor temperature of 50°F, whereas the heating load would be at least twice as great at the lower temperature. This graph shows why most air-to-air heat pumps incorporate supplementary resistance heaters in the indoor unit to augment the compression system during the coldest

weather. In five houses studied at Seymour Johnson Air Base, the compression system provided 51 to 82% of the heat requirement, and in an equal sample at Columbus Air Base the compression system provided 99 to 116% of the heat requirement at design outdoor conditions in each case. Current military specifications require that the heating capacity of the compression system should be at least 60% of the heat loss of a house at design outdoor temperatures.

Figure 3 illustrates the concept of the balance point for a heat pump, by plotting compressor running time against outdoor temperature. For this particular installation at an air base in North Carolina, the heat pump ran continuously at any outdoor temperature below 32°F. The balance point is not a precise temperature in any given combination of house and heat pump because of the effect of wind and sun on the heat loss and the heat released by other equipment inside the house.

When a heat pump is used for heating, the amount of heat delivered from the indoor heat exchanger is approximately equal to the sum of the heat absorbed in the outdoor heat exchanger and the heat equivalent of the electric energy used by the unit. The ratio of the heat delivered indoors to the electric energy used by the unit, expressed in the same units, is called the heating coefficient of performance of the heat pump. The cooling coefficient of performance is the ratio of the heat absorbed indoors to the electric energy used by the unit, expressed in the same units. These ratios decrease as the indoor-outdoor temperature difference increases. Figure 4 illustrates this relationship during laboratory tests of two types of heat pump. This figure shows that the heat delivered indoors by these heat pumps was about twice the heat equivalent of the electric energy used at an outdoor temperature of 30°F, and that the heat absorbed indoors at an outdoor temperature of 95°F was also about twice the heat equivalent of the electric energy used.

Figure 5 illustrates the coefficient of performance obtained in an actual installation of a split system at an air base in which the indoor unit was located in the attic. In this installation the coefficient of performance as measured at the unit increased only slightly with rising outdoor temperature. This was thought to be partly due to the fact that the heat stored in the system during the running periods was not appreciably recovered during the inoperative periods during intermittent operation. This was a characteristic of the attic distribution system.

Figure 5 also shows the effect of air leakage into the air distribution system on the system performance factor. Due to poor workmanship in the duct system and the use of some structural spaces as return air passages, considerable cold attic air was drawn into the return air ducts. This air leakage, which was not the fault of the heat pump unit, reduced the useful heating effect of the heat pump. It emphasizes the need for specification requirements and field tests at the time of installation to provide an acceptable quality of design and workmanship for the air distribution system.

The electric energy used throughout the year in each of five sample houses at three air bases by the heat pump and the other major appliances was observed during one of the field studies. The average annual energy used in these fifteen houses is summarized in Table 1. This table shows that half of the total electric energy used throughout the year was consumed by the heat pump and bathroom heater, and an equal amount was used for water heating, cooking, clothes drying and miscellaneous devices. The energy used for cooling was about two-thirds of the total used for heating. A little more than a fourth of the total was used by the water heater. Since the average cost of energy at these three bases was about 0.8¢/KWH the annual cost for heating and cooling averaged about $100 per house.

The analysis of the energy usage in 16 houses at Little Rock Air Base indicated an energy usage factor for the heat pump during both cooling and heating operation of 2.1 KWH/degree-day (1000 sq ft of floor area) when the degree-days were related to an outdoor temperature of 65°F in both seasons. The corresponding factors during heating operation at two other air bases averaged2.4 and 1.7, respectively. These figures may be used for estimating energy requirements for heat pump applications in houses of similar construction and occupancy. However, the factor would be expected to vary with number of stories in the house, degree of insulation, and living habits of the occupants.

At many of the air bases where heat pumps were used, the unit cost for electric energy depended not only on the total monthly usage but on the maximum demand of the whole housing area during any single 15-minute or 30-minute period. A detailed analysis of the daily pattern of power demand in five sample houses at Little Rock Air Base revealed that the monthly maximum demand was not directly caused by the heating equipment during the coldest hours of the 24-hour period, but was usually brought about by the use of other electrically-powered equipment by the occupants during their daily activities in the house. Figure 6 shows the average 15-minute demand throughout the day for a 30-day period in January and February for a 3-bedroom house, and the maximum and minimum 15-minute demands for any one day of the month. Figure 7 shows similar data during a month in August under cooling operation.

Figure 6 shows that the average and maximum power demands rose quickly about 8:00 a.m. and remained at a high level until 1:00 to 2:00 p.m. when it decreased to values only a little above night time demands. After 2 or 3 hours at a low value, the power demands rose to a smaller maximum at 6:00 to 7:00 p.m. and then gradually decreased to a night level before midnight. It should be noted that the maximum demand during any one day of the month was more than twice the average for the whole month.

The daily pattern shown in Figure 7 for a summer month has characteristics similar to the winter pattern, except there was no period of low demand in the middle of the afternoon during summer operation, probably because the high solar load in the afternoon required fairly steady operation of the heat pump.

TABLE 1

AVERAGE ANNUAL ENERGY USED IN SAMPLE HOUSES AT THREE AIR BASES

Component of Load	Total Energy Used	Percent of Total
	KWH	
Heat Pump		
Cooling	5,170	19.7
Heating, Compressor	5,830	22.2
Heating, Supp. Heaters	1,440	5.5
Total	12,440	47.4
Bathroom Heater	780	3.0
Water Heater	7,230	27.5
Cooking Range	1,100	4.2
Clothes Dryer	1,200	4.6
Miscellaneous	3,490	13.3
TOTAL	26,240	100.0

The maximum electric power demands for the 16 individual houses studied at Little Rock Air Base averaged about 14 KW in the summer and about 17.5 KW in the winter, with the heat pump, water heater, and miscellaneous devices being the principal contributors to these maximum demands. These results indicate that a programming device which reduced the degree of coincident operation of the various appliances would lower the maximum demand and thereby the average unit energy cost. Of the many mechanical-electrical devices available for programming a group of component loads in a house, it appeared that a relay which permitted one or more appliances to be energized only if the load already energized was below some selected value offered the best possibility for reducing the maximum power demand with least inconvenience. This type of control is now being installed on a pilot basis in a group of houses at one air base to explore its effectiveness and the potential inconvenience to the occupants.

Information obtained from the engineering offices at the various air bases during and since the field studies of heat pump performance showed that the replacement of motor-compressor units in the air-to-air heat pumps was much higher than was anticipated by the manufacturers. Data for a 6-month period in 1965 showed that the failure rate of motor-compressor units in the heat pumps at eight air bases ranged from 5 to 10 percent of the total number of installations at each air base. Similar records for the motor-compressor units in conventional air conditioners used in U. S. Air Force housing projects ranged from 4 to 10 percent during the same period. Thus it appears that the failure rate was not significantly different among contemporary heat pumps and air conditioners.

In order to investigate the mode of failure of the motor-compressors in air-to-air heat pumps thirty-five hermetic units that had been replaced at 7 air bases were cut open and inspected at the National Bureau of Standards. The 5 compressors from each air base were a group that were received in sequence at the repair shop after receiving the request from the Bureau for units that had failed. No internal inspection was performed at the air bases. The 35 specimens comprised 8 models from 4 manufacturers. The following kinds of defects or failures were observed. Some units exhibited more than one defect.

Burned and/or grounded windings	46%
Broken wires and burned control contacts	20%
Bearings, connecting rods, cylinders worn, scored or seized	34%
Other mechanical defects	9%
Undetermined defect	3%

This summary indicates that 66% of the specimens revealed electrical defects and 43% revealed mechanical defects. However, these data do not establish the basic cause of failure. About half of the units with burned or grounded windings revealed general charring of the electrical insulation whereas the other half showed only localized overheating.

Other laboratory work that has been carried out relative to correction of the motor-compressor failure problem include an investigation of the properties of the compressor oil as an indicator of impending failure, the development of reliable field methods for removal of moisture and air from the refrigerant circuit during installation and repair, and the use of a liquid accumulator at the compressor inlet to prevent liquid refrigerant from entering the cylinders. The acceptance tests of commercial models of heat pumps employing capillary tubes as refrigerant flow controls revealed that liquid refrigerant consistently entered the compressor during heating operation at outdoor temperatures of 20°F or lower. The study of the causes of compressor failure is continuing at the Bureau and extensive consultations with manufacturers are in progress to provide the basis for revising and strengthening the specification requirements for the system design of heat pumps. The manufacturers of air-to-air heat pumps are now fully aware of the high incidence of motor-compressor failure and are seeking causes and cures for this problem.

In the course of implementing the air defense of the country, the U. S. Air Force has installed air-to-air heat pumps at 8 air bases and a combination of a gas heating system and an electric air-conditioning unit at a number of other sites to provide year around air conditioning of family housing. The choice of system has been based on economic factors of first cost, operating cost, and maintenance cost even though it is generally recognized that sufficient reliable data do not exist for satisfactory decision-making.

Against this background the National Bureau of Standards was asked to make field measurements of the annual energy usage in five houses at each of six air bases, half of which employed all-electric air-to-air heat pumps and the other half gas heating and electric cooling systems. Figure 8 is a comparison of the actual energy used for heating, cooling, water heating, cooking, clothes drying, and miscellaneous purposes at each of the six air bases. The energy is expressed in both kilowatt hours and therms and both vertical energy scales apply to all the bar graphs. This figure shows that the energy used for heating with a gas furnace is much higher than that used by an electric heat pump. Likewise, the energy used by the gas water heaters and gas ranges exceeded that used by the corresponding electric appliances by an appreciable amount. On the other hand the energy used for cooling, for clothes drying and for miscellaneous purposes was about equal in the two groups of houses. The legend of Figure 8 shows that there were some differences in floor area, and in cooling and heating degree-days at the various air bases, and a considerable variation inthe unit costs of gas and electric energy.

In order to make the best economic comparison possible with the available data the actual energy costs at the six air bases were adjusted for a floor area, and heating and cooling degree-days equal to the average of all sites in direct proportion. Likewise, the unit energy cost for the all-electric houses was adjusted to an average value for the three bases using heat pumps, and for the other group of houses, to the average cost of gas and electricity, respectively, at the three bases using the combination system. A comparison of these adjusted values is shown in Figure 9. The average adjusted annual energy cost for the 15 sample houses employing gas-electric combination systems was 90 percent of that for the 15 sample houses employing air-to-air heat pumps. Figure 9 also shows that the cost of water heating was significantly less with gas than with electricity and the cost for cooling and miscellaneous devices was appreciably higher at the sites employing gas furnaces simply because the unit cost of the electric energy was higher at these sites where it was used only for cooking, lighting, and clothes drying.

It should be pointed out that the comparisons made in Figure 9 do not account for variations in degree of insulation, amount of window area, infiltration rates, solar radiation, wind velocity, and living habits that may have existed for the two groups of houses that are being compared.

Not all of the significant investigations and useful results on air-to-air heat pumps that have been developed during this program could be described in this brief review. Additional information is available in the published papers referenced. There is little doubt that the U. S. Air Force has contributed significantly to the development of fully air-conditioned military housing of good quality in which the total annual utility cost is moderately low and that the National Bureau of Standards has assisted the defense agencies in becoming informed purchasers. This program has also served to challenge the heating and air conditioning industry to meet its responsibilities in design, manufacturing, and installation practices in residential construction.

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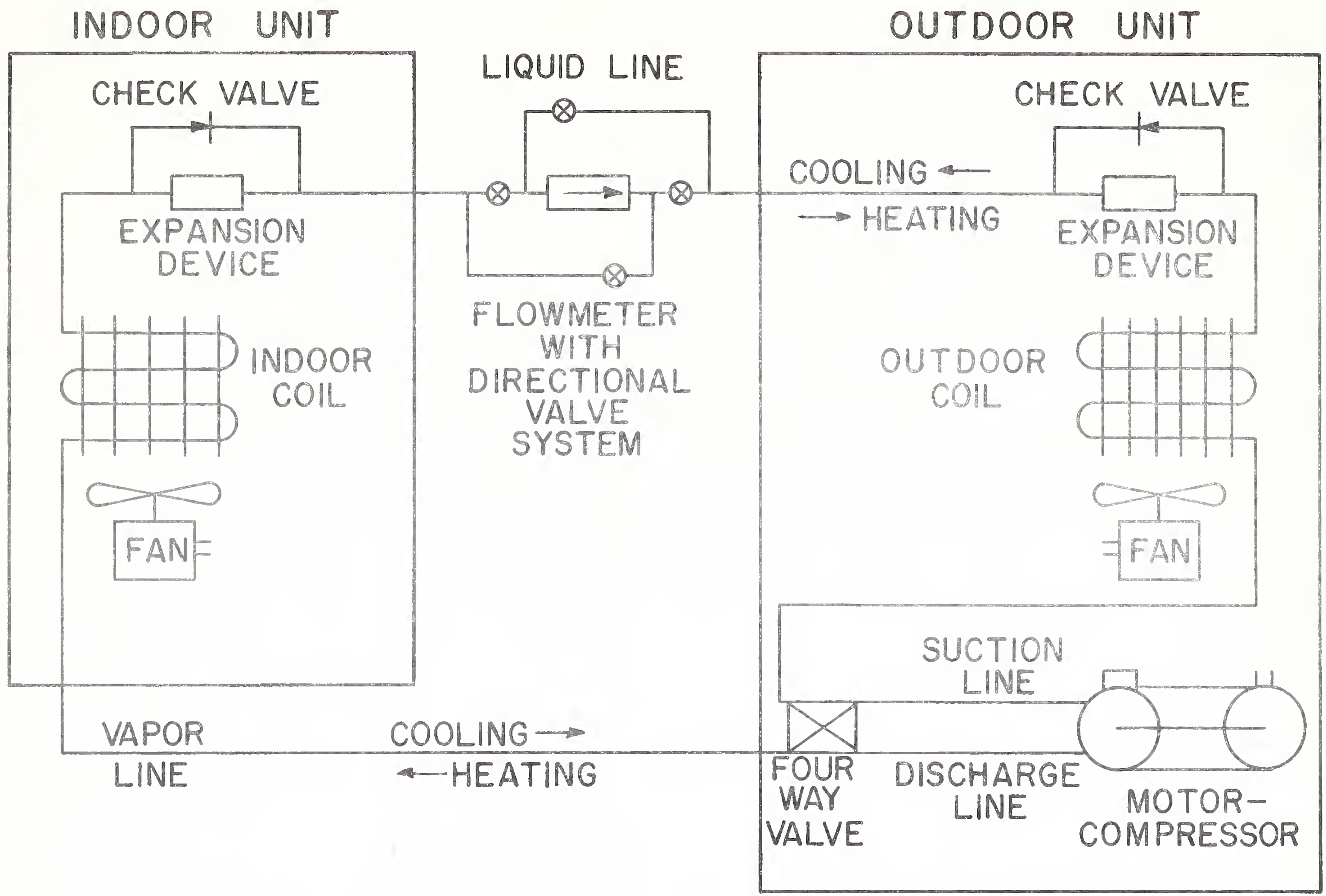


FLOW DIAGRAM FOR HEAT PUMP TESTS

FIG. 1

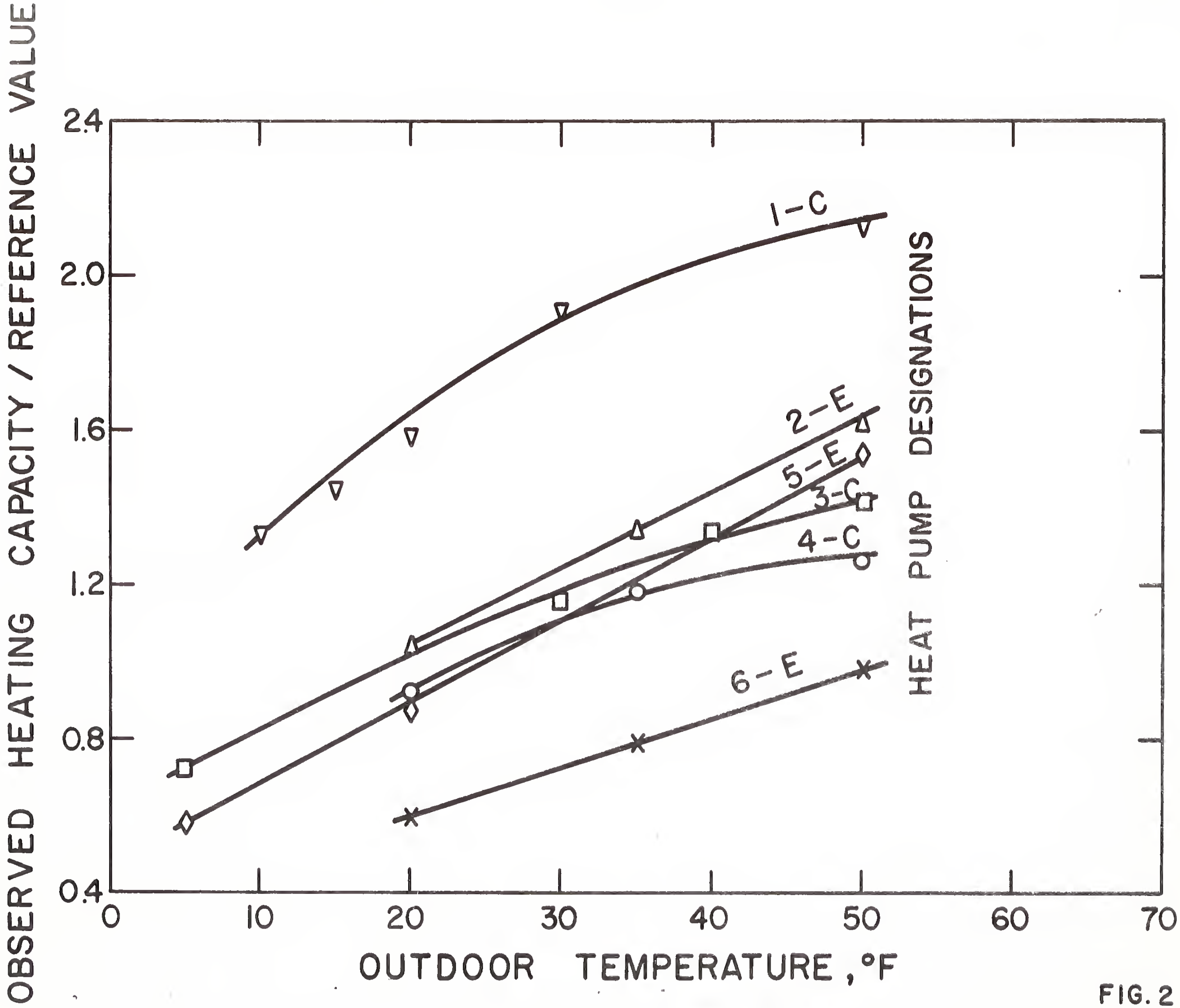


FIG. 2

Effect of outdoor temperature on heating capacity of six heat pumps at constant indoor temperature of 70°F.

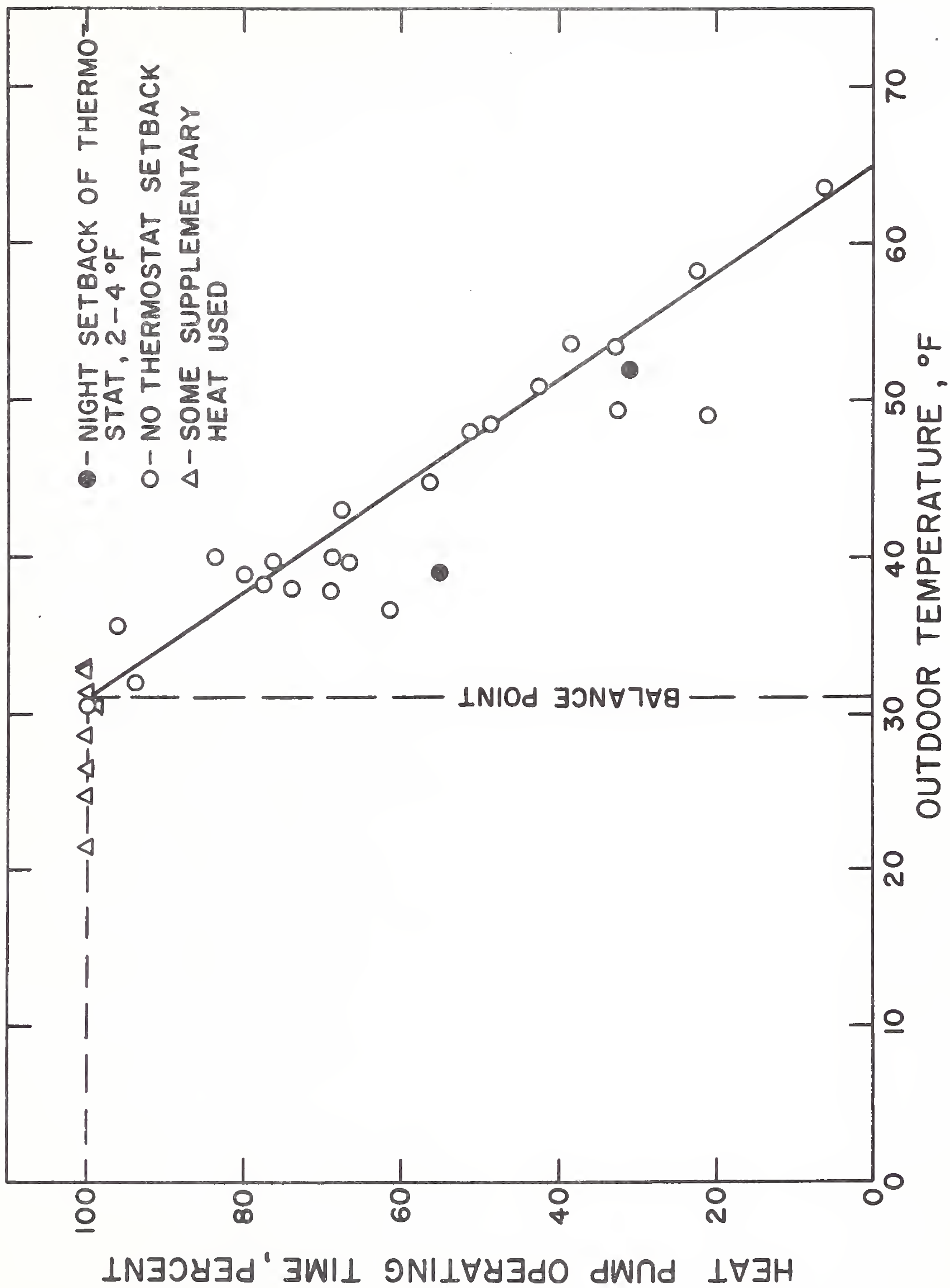


Fig. 3 Operating time and balance point for the heat pump in a 3-bedroom house at Seymour Johnson Air Base.

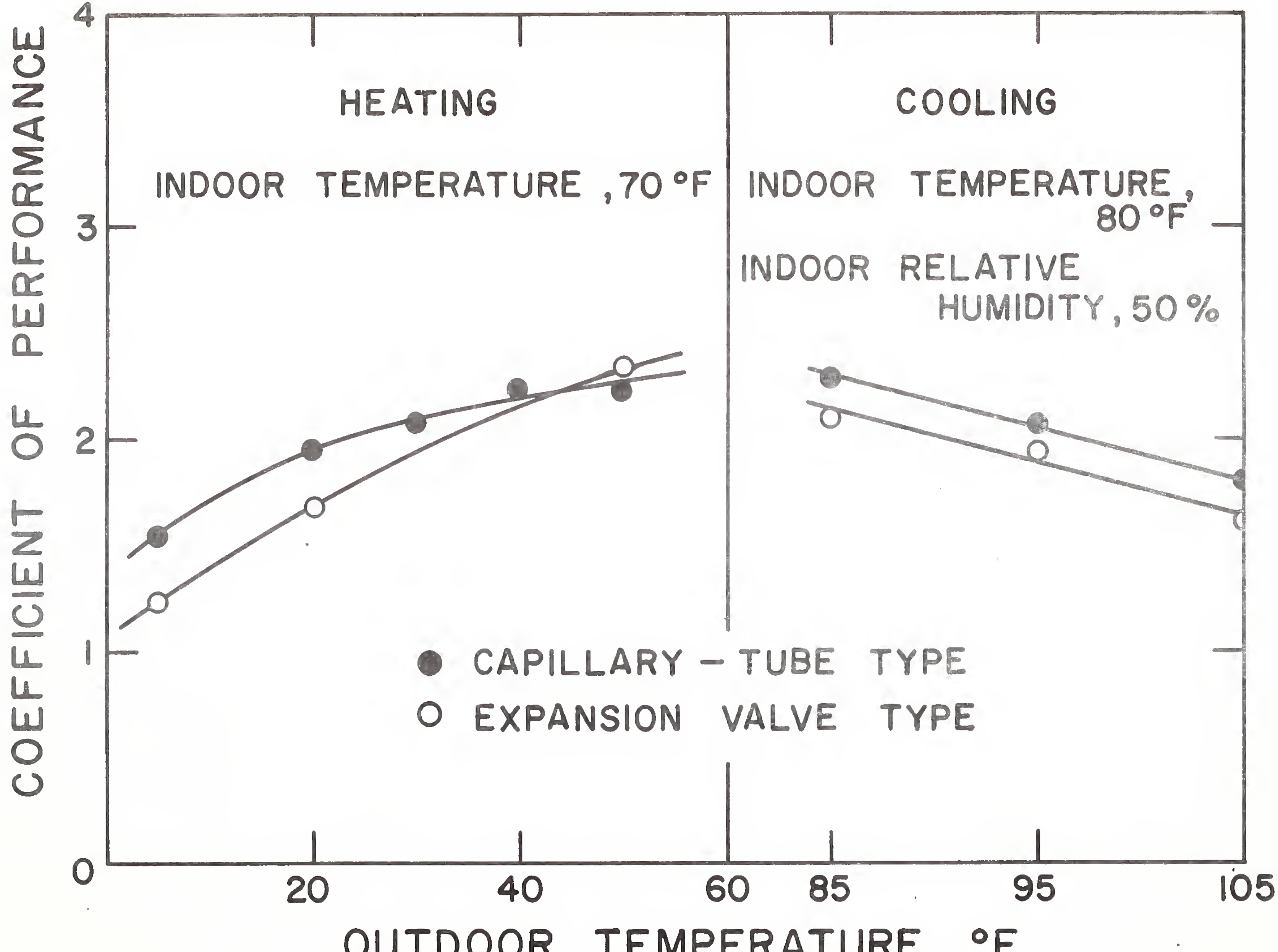


FIG. 4

The relation of coefficient of performance to outdoor temperature for two types of heat pump for heating and cooling at constant indoor conditions.

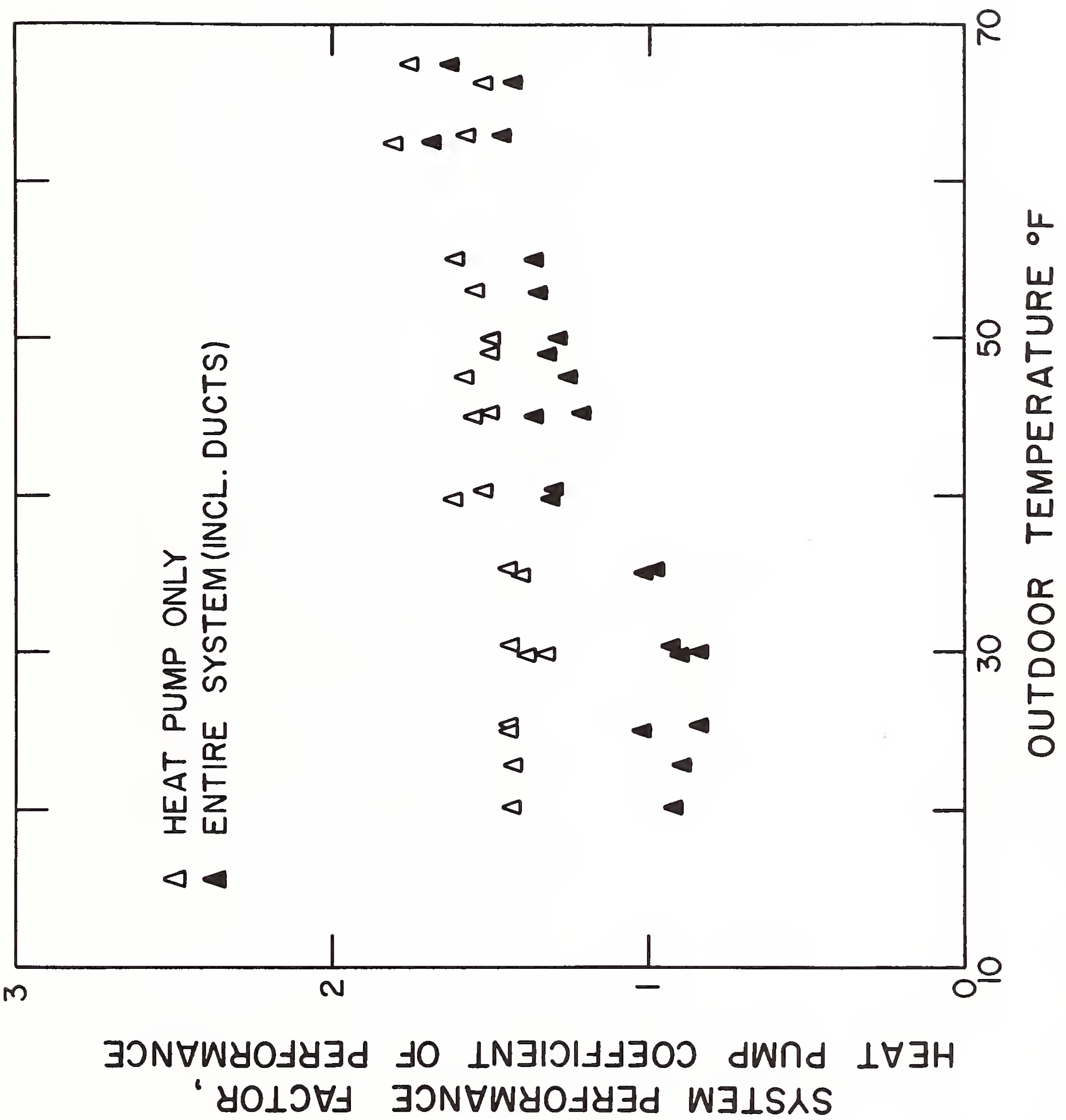


Fig. 5 Heat pump coefficient of performance and system performance factor for 2-bedroom house at Seymour Johnson Air Base for a range of outdoor temperature.

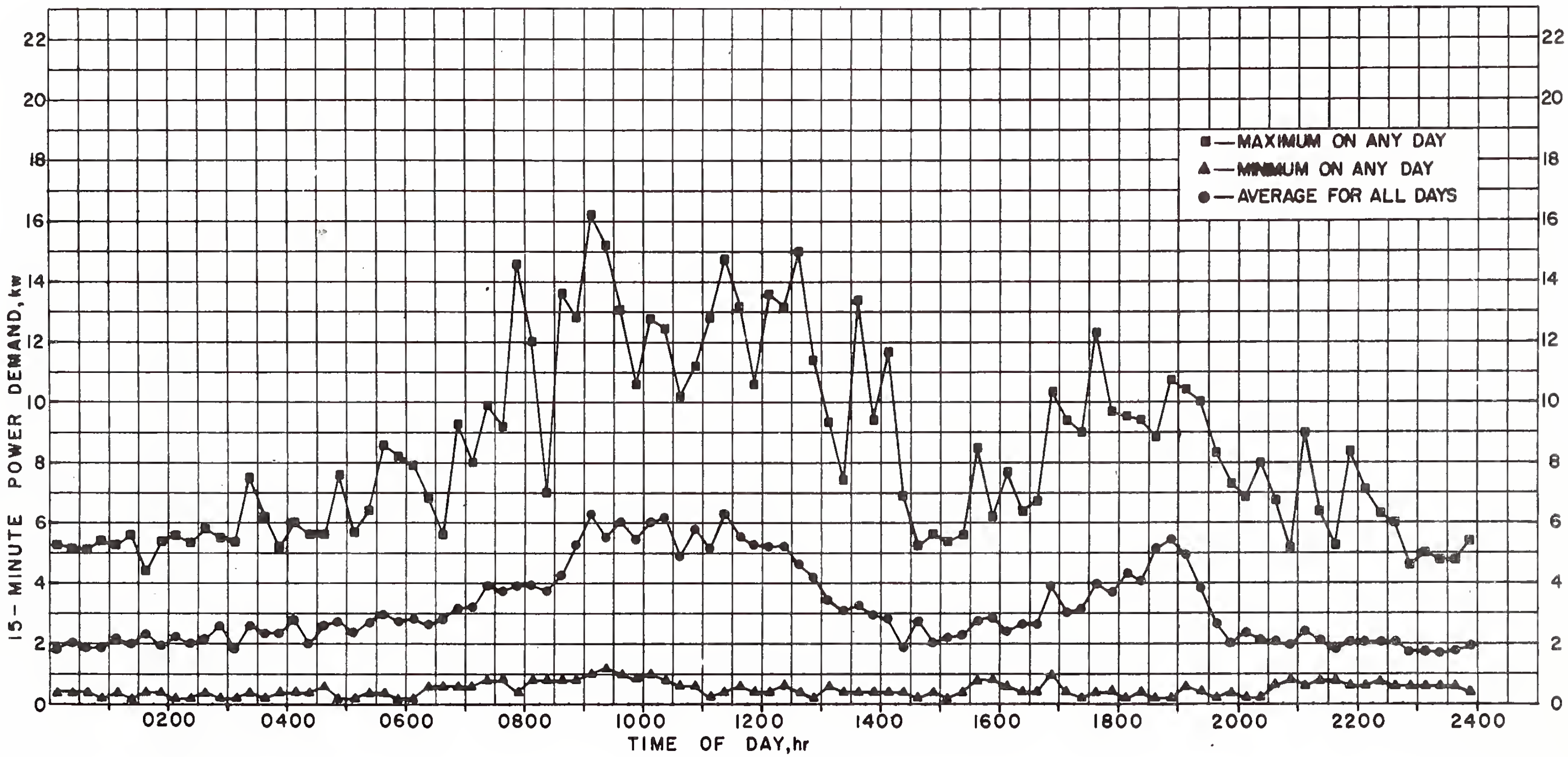


Fig. 6 Daily pattern of power demand in a 3-bedroom house at Little Rock Air Base for the period Jan. 8 to Feb. 8, 1960.

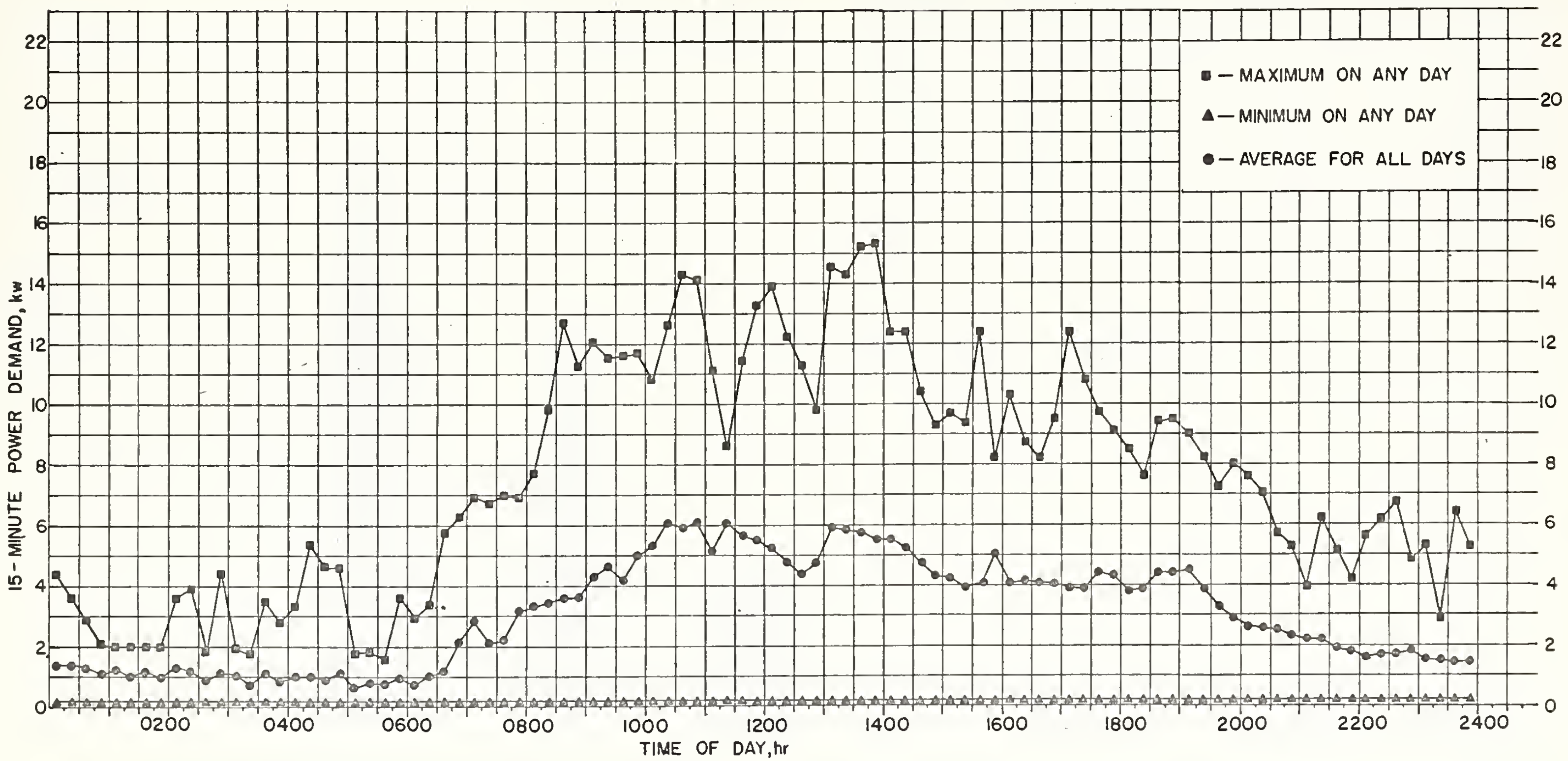
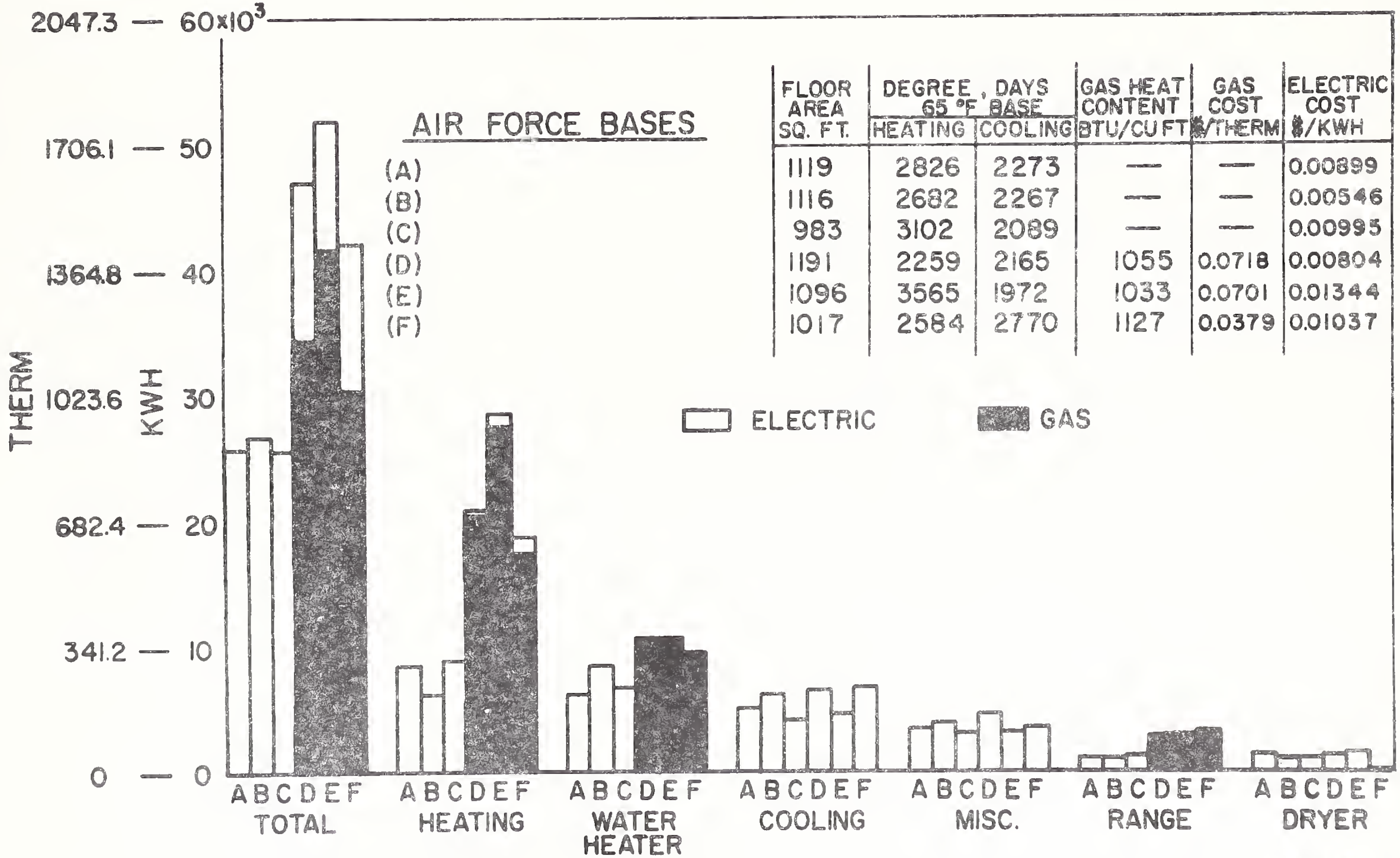


Fig. 7 Daily pattern of power demand in a 3-bedroom house at Little Rock Air Base for the period Aug. 7 to Sept. 8, 1959.

ENERGY USAGE

MAY, 1960 THROUGH APRIL, 1961 AVERAGE OF FIVE HOUSES EACH AT SIX AIR BASES



AIR FORCE BASES	FLOOR AREA SQ. FT.	DEGREE, DAYS 65 °F BASE HEATING	DEGREE, DAYS 65 °F BASE COOLING	GAS HEAT CONTENT BTU/CU FT	GAS COST $/THERM	ELECTRIC COST $/KWH
(A)	1119	2826	2273	—	—	0.00899
(B)	1116	2682	2267	—	—	0.00546
(C)	983	3102	2089	—	—	0.00995
(D)	1191	2259	2165	1055	0.0718	0.00804
(E)	1096	3565	1972	1033	0.0701	0.01344
(F)	1017	2584	2770	1127	0.0379	0.01037

FIG. 8

ADJUSTED ENERGY COST

MAY, 1960 THROUGH APRIL, 1961 AVERAGE OF FIVE HOUSES EACH AT SIX AIR BASES

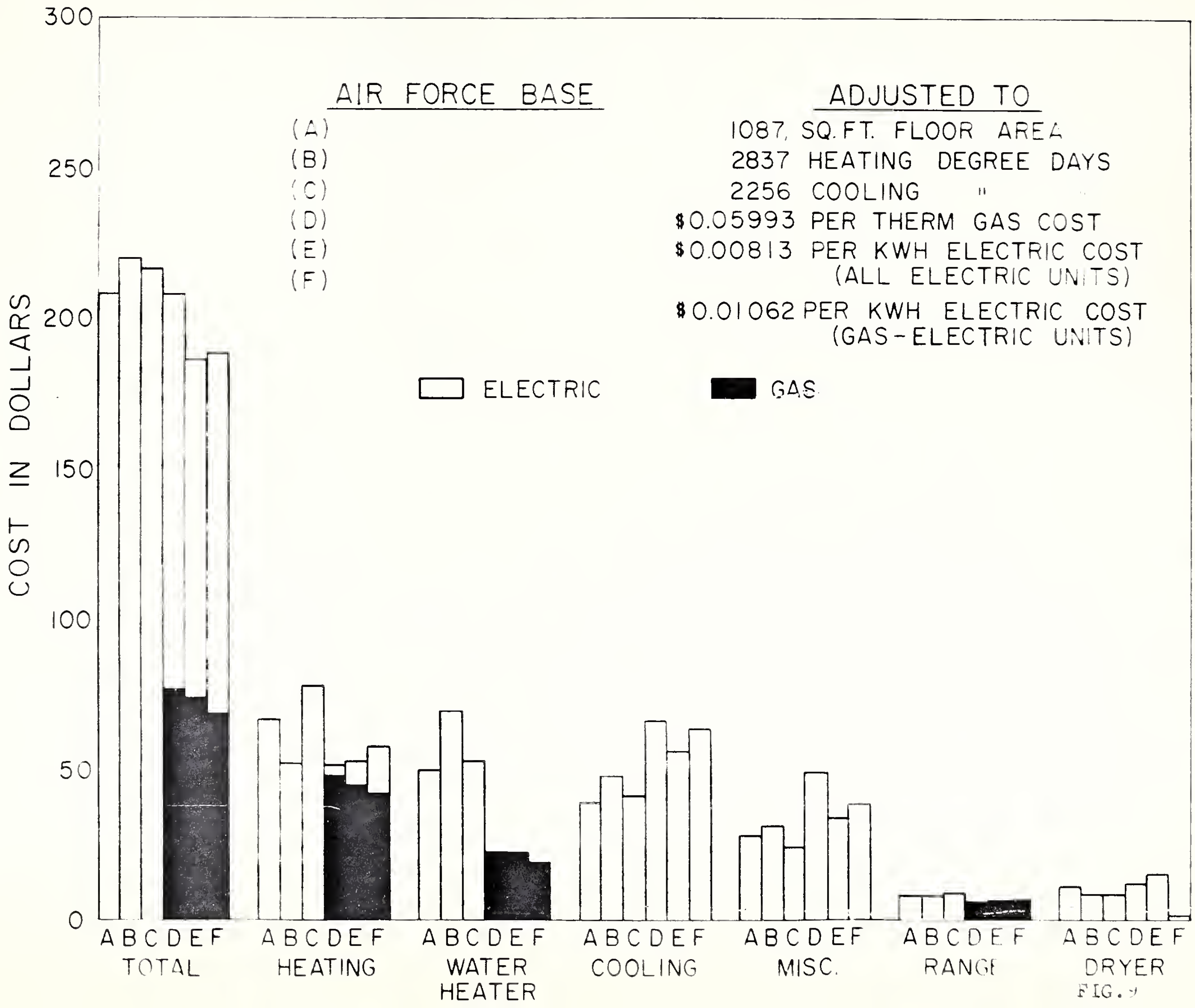


FIG. 9